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The Application of Radar and Thermography to Bridge Deck Condition Surveys

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Abstract: This paper summarizes the theoretical and practical aspects of the application of radar and thermography to bridge deck condition surveys. A prototype vehicle was developed. The radar wave forms and the thermographic images were calibrated in the field to various forms of physical distress. It is shown that radar and thermography are useful tools for assessing the condition of bridge decks and that the two technologies are complementary; thermography is most useful for locating subsurface defects on exposed concrete surfaces, and radar is most applicable to detecting defects in concrete deck slabs which have a bituminous surfacing.

Comments: State-of-the-art report on the DART prototype vehicle.

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1/ Introduction

An effective bridge management system requires a comprehensive data base. At the network level, the data are needed in order to assess the overall condition of the bridge network and to predict the effect of alternative preservation and improvement actions. At the project level, more detailed data are required to select the most appropriate method of rehabilitating a particular structure and to prepare the contract documents.

Collecting data on the condition of bridges by traditional methods is expensive and the results are not always dependable. In the late 1970's, research studies were initiated by the Ontario Ministry of Transportation to develop rapid and reliable methods for collecting data on the condition of bridge decks. The studies were part of a larger program to improve the technology for rehabilitating bridges [1].

The first studies were conducted on exposed concrete decks and were designed specifically to investigate methods of detecting delamination caused by the corrosion of embedded reinforcement. It was found that infrared thermography was an effective method of detecting delamination over a wide range of ambient temperatures [2]. During the period 1980-2, the studies were extended to investigate methods capable of detecting deterioration in concrete deck slabs which have a surfacing of bituminous concrete. Over 90% of the bridges in Ontario now have a waterproofing membrane and two 40 mm thick lifts of bituminous surfacing. A test site was constructed by selecting a typical bridge which was exhibiting corrosion-induced distress, surveying the bridge and then paving it without first making repairs. Areas of scaling and debonding were simulated prior to paving. The capabilities of eight techniques to detect the locations and types of deterioration in the test deck were evaluated. The most promising techniques were found to be radar and thermography [3].

Further research concentrated on developing automated processing techniques to analyze the thermograms and radar waveforms and present the results in a form usable by bridge engineers. The product of this work was a self-contained vehicle named DART (Deck Assessment by Radar and Thermography) which, as the acronym implies, is equipped with both radar and thermography [4]. This paper summarizes the theoretical and practical aspects of the development of the DART prototype vehicle and describes the experience in its use under operational conditions.

2/ Major Types of Deterioration in Bridge Decks

The most serious form of deterioration in bridge decks in North America is that caused by corrosion of embedded reinforcement. As the reinforcement steel corrodes, it expands and creates a crack or subsurface fracture plane in the concrete at, or just above, the level of the reinforcement. The fracture plane, or delamination, may be localized or may extend over a substantial area.

Scaling, which is a breakdown of the cement-paste matrix, is also a serious problem wherever it occurs. The disintegration of the concrete, which is caused by the freezing of concrete critically saturated with water, begins at the surface and gradually progresses so that the full depth of the deck slab may be affected. It is most common in older bridges which do not have an effective air void system.

On asphalt-covered decks, bond failure may occur between the concrete deck and bituminous surfacing. Debonding can result in moisture being trapped on the surface of the concrete and, where thin surfacings are used, can lead to failure of the bituminous surfacing. Although the consequences of debonding are not as serious as either delamination or scaling, it can be confused with these two phenomena in surveys. Consequently, it is important to be able to identify and define debonded areas.

3/ How Thermography and Radar Detect Deterioration

3.1/ Thermography

Infrared thermography is a remote method of measuring the surface temperature of an object. Consequently, the detection of deterioration by infrared thermography is based on the difference in surface temperature that exists between deteriorated and sound concrete under certain atmospheric conditions. Concrete is a poor conductor of heat and the surface temperature differences develop as a result of different rates of heat transfer occurring inward from the surface. The surface, as it is being irradiated with solar radiation, is presumed to receive a uniform heat flux. Discontinuities which impede the conductive heat flow from the surface, such as a delamination or debonding, will result in a higher surface temperature during periods of heating. The reverse is true during periods of cooling which occur mainly at night. Because of the breakdown of the matrix, scaled concrete has a different coefficient of thermal conductivity than sound concrete which also results in a difference in surface temperature.

The differences in temperature have been confirmed by implanting thermocouples in deck slabs and by the direct measurement of surface temperatures over known areas of sound and deteriorated concrete [2,3]. Measured temperature differences were also compared with a theoretical heat transfer model as a means of establishing operational constraints on the use of thermography for bridge deck surveys. An approximate solution of the general equation for transient heat flow [5] indicated that the most critical parameters affecting temperature differentials are solar irradiance and emissivity. However, wind speed is also critical to the theoretical calculation of emissivity.

Delaminations appear as well defined white areas which are hotter (during daylight hours) than the surrounding areas of solid deck which are cooler and appear dark.

Scaling of concrete beneath a bituminous surfacing produces a characteristic thermal image which is a mottled grey-white tone. The more severe and extensive the scaling, the more mottled the thermal image appears.

Debonding is not easily identified by infrared thermography. Depending upon the depth of any delaminations, debonding may appear hotter or identical to the delaminations, and, at other times, may go undetected.

3.2/ Radar

The detection of deterioration by radar is based on reflections of a high frequency electromagnetic wave caused by changes in the electromagnetic properties of the material being probed. Whenever a transmitted wave encounters an electromagnetic discontinuity (deterioration) or change of material dielectric, it is partially reflected. The patterns created by the reflected waves are received by the radar antenna. The radar receiver takes a measurement of the time required for the transmitted pulse to travel to a target discontinuity and for the reflected pulse to return [4]. The time delay of the radar echo from a structural discontinuity is directly related to the depth of the fault.

The impulse radar used in the DART system has been described in detail elsewhere [6]. The radar is monostatic with the antenna design being based on a constant flare angle, variable-width open horn. The transmitted signal is a pulse which has a duration of approximately 1 ns and a repetition rate of 5 million pulses per second.

The reflected signal is sampled much like in a sampling oscilloscope using the sliding gate technique, and averaged, producing an output voltage pulse waveform of approximately 1 ms duration suitable for processing by conventional means. The actual transmitted radar waveform, shown in Figure 1, is obtained by positioning the radar antenna directly over a thin aluminum plate placed on the bridge surface and obtaining the reflection. The signal has a duration of approximately 0.9 ns between negative peaks P and Q with the main positive peak at A. The peak at A represents the surface reflection from the aluminum plate and calibrates the system for reflections from the bridge surface. The transients at the beginning and end of the main pulse restrict the resolution in measuring the thickness of a material. Also, the response after point R is very small, indicating the variations due to discontinuities can be detected in this region without too much interference.

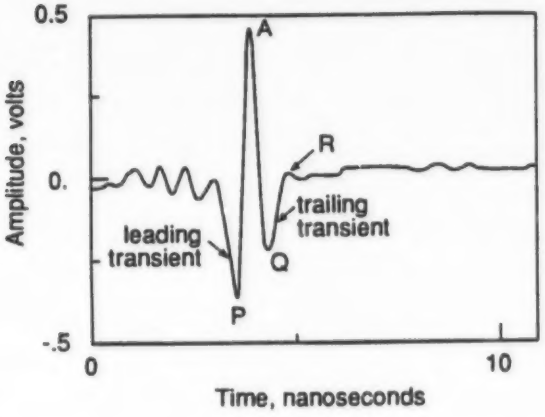

Figure 1/ Waveform reflected from a metal plate on the deck surface

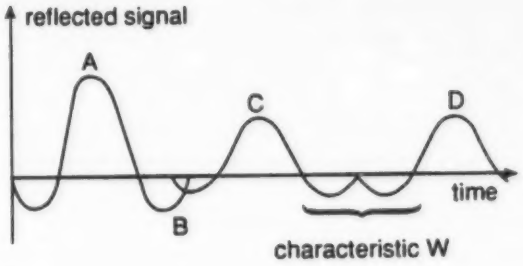

Figure 2/ Theoretical reflections from a sound bridge deck

It is possible to gain some insight as to the type of waveforms to be expected by simply considering the transmission and reflection of the radar impulse travelling from air into asphalt into concrete and reflecting from the reinforcing bars (rebars). When the incident electric field reflects from the asphalt surface, there is a 180 °phase shift, since the dielectric constant of asphalt (approximately 3.7) is higher than that of air (1.0). The incident wave propagates through the asphalt, resulting in another reflection at the asphalt-concrete interface, again with a 180° phase shift relative to the incident wave since the dielectic constant for concrete (approximately 6) is higher than that of asphalt. The incident wave continues to propagate through the concrete to the layer of rebars where a third reflection occurs, also with a 180° phase shift relative to the incident wave. Since the rebars normally form a grid with a spacing of approximately 200 mm between bars, most of the power passes through the matte resulting in an observed reflection coefficient of approximately -0.1 to -0.4 (depending on whether the antenna is over the bar or over a space between bars) as determined by measurements on sample test blocks.

These measurements on test blocks also showed that propagation through the asphalt and concrete is nearly lossless. However, there is a certain amount of spherical spreading and scattering that reduces the amplitude of the signals reflected from the asphalt-concrete interface and the rebars. For the asphalt-concrete interface, all of these sources of loss can be taken into account by a calibration factor, which compensates for the actual bridge structure under consideration. Thus, the three reflections are illustrated in Figure 2 where the peak at A represents the reflection from asphalt, the peak at C is produced by the asphalt-concrete interface, and the reflection at D is from the rebars. Although the reflections are shown as being quite distinct, there may be considerable overlap of the transient portions

of the waveforms such as at point B. However, this is not a serious problem provided that the main peaks are well defined. (There are further reflections bouncing between the layers, but these are ignored since they are small compared to the primary reflections, and normally occur later and are not seen in the first portions of the waveform.)

The thickness of the asphalt is determined by measuring the time between point A and point C taking account of the dielectric constant of asphalt. Also, it is seen that the reflections from the asphalt-concrete interface and the rebars produce a W-shaped waveform which is called the characteristic W. This characteristic W is useful in identifying the difference between good and delaminated concrete.

The reflection coefficients can be calculated, assuming lossless material, by the relation:

$$p = \frac{Z_L - Z_S}{Z_L + Z_S}$$

where Z_L is the load impedance and Z_S is the intrinsic impedance of the source medium.

The radar reflection from a sound bridge deck is illustrated in Figure 3. The peak at A represents the surface reflection from the asphalt, the peak at C indicates the reflection from the asphalt-concrete interface, and the peak at D is the reflection from the rebars. The transients observed in Figure 1 obscure the first part of the reflection from the asphalt-concrete interface; however, the peak at C is still well defined.

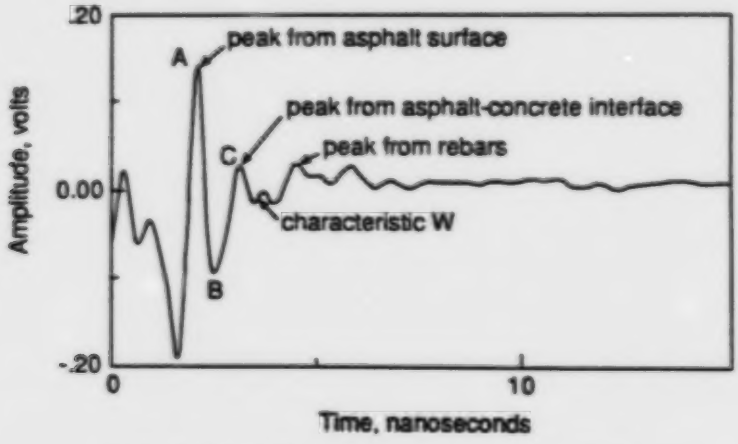

Figure 3/ Actual reflection from a sound bridge deck

For analysis, two ratios are defined, the first being R1, the ratio of magnitude at point B to magnitude at point A, where point B is defined to be the first negative going peak after peak A. The second ratio, R2, is the ratio of magnitude at point C to magnitude at point A where point C is defined to be the first positive going peak after point B. These two ratios have different uses.

For a sound deck, R2 is approximately 0.28 which is somewhat less than calculated (0.316) but this is due to the various losses, scattering and spherical spreading. Taking the ratio of these two R2 values provides the calibration factor, for the signal strength calculations of real signals at the asphalt-concrete interface with fault conditions. R1 results from a combination of the transients of the surface reflection and the reflection from the asphalt-concrete interface.

Debonding

Since debonding affects the interface between the asphalt and the concrete, the reflection from the asphalt surface will remain essentially unchanged. However, the reflection from the asphalt-concrete interface will be altered producing a reflected waveform with either increased or decreased magnitude at point C depending on the material filling the gap. This gap will effectively change the R1 and R2 ratios of the radar waveform.

Scaling

Scaling of the concrete influences the interface gap reflectivity depending on whether the gap is water or air filled. In this case, the gap is much larger than occurring in debonding. For the purposes of modelling, it is assumed that the reflection from the gap is due to a single reflection from the asphalt-gap interface. With air in the gap, the reflection not only changes polarity, compared with a good asphalt-concrete interface, but the magnitude of the R1 ratio is increased substantially. With water in the gap, the polarity remains the same, but the R2 ratio is much larger. Since it is not known whether the scaled concrete contains air or water, both the R1 and R2 ratios are calculated and a search made for values larger than normal.

Delamination

Delamination occurs in the region between the surface of the concrete and the top mat of steel. There may be one or more fracture planes in the concrete containing air or water resulting in at least one discontinuity between the concrete surface and the rebars. The additional reflections from the delamination mean that the characteristic W present in good structure is no longer present.

The range of values used for evaluation are as follows:

	R1	R2
Good	<0.40	<0.28
Debonded	<0.40	>0.28
Scaled	>0.40	>0.28

A further attribute of the signal processing is that the thickness of asphalt d_1 is simply the product of the time delay T_A between points A and C, and the velocity of propagation in asphalt $\left(\frac{C}{\sqrt{\varepsilon_A}}\right)$ where C is the velocity of light, ε_A is the dielectric constant of the asphalt, and

$$d_1 = \frac{T_A C}{\sqrt{\varepsilon_A}}$$

Since the sampling rate used for the radar signal is 25000 samples per second (40 μs per point), the thickness of asphalt in millimeters becomes

$$d_1 = \frac{6 * M}{\sqrt{\varepsilon_A}} \text{mm}$$

where M is the number of samples between points A and C. Results show that if the asphalt (with ε_A = 3.7) thickness exceeds 50 mm, there should be little difficulty in evaluating d_1, due to the transients of the waveform. Actual comparison of radar measured asphalt thickness and core samples show an accuracy of approximately ±5 to ±8% when the asphalt thickness is in the 70 to 100 mm range.

The dielectric constant of asphalt can be calculated by first measuring the reflection coefficient of air-asphalt interface. The reflection coefficient is the negative of the ratio of the amplitude at point A in Figure 2, divided by the amplitude at point A in Figure 1. Thus,

$$\rho_1 = \frac{-x_2}{x_1} \quad (4)$$

Once the value of ρ_1 is determined, ε_A is calculated from the relation

$$\varepsilon_A = \left[\frac{1 - \rho_1}{1 + \rho_1}\right]^2 \quad (5)$$

It is important to note that, since ε_A varies from bridge to bridge, it is calculated from field measurements.

The dielectric constant of concrete cannot be measured so easily since scattering and spherical spreading losses affect the amplitude. However, the thickness of concrete over the rebars can be estimated by noting the time delay between points C and D, using an assumed value of ε_C.

4/ The Dart Prototype Vehicle

The exterior and interior of the DART vehicle is shown in Figures 4 and 5 respectively. The essential features of the unit are as follows:

i) A hydraulically-operated telescopic mast mounted on the front of the vehicle. The mast is lowered for attaching the infrared scanner and refilling the liquid nitrogen. It is raised to its operating height of 5 m.

ii) The infrared scanner. When equipped with a 20° lens and operated at an angle of 45° and height of 5 m, the scanner is capable of viewing the width of one complete traffic lane at a single pass. The scanner is connected through a control unit to an interface unit which converts the scanner's European standard (PAL) signal to the North American (NTSC) standard. The output is then fed to a high resolution video tape recorder.

iii) The radar antenna is attached to a rail on the front of the vehicle using a sliding bracket so that it can be positioned anywhere within the width of the vehicle. The mounting height of 150 mm results in an elliptical footprint of 300 x 175 mm on the deck surface. The transmitter and receiver are also mounted on the sliding bracket. Returning radar echoes are received by the antenna and transmitted to the control unit inside the vehicle. The waveform is simultaneously displayed on an oscilloscope and recorded on a seven-channel FM tape recorder. The operator can monitor the signal from the control unit and from the tape recorder, thus permitting a check of the quality of the signal before and after recording.

iv) A fifth wheel is attached to the rear of the vehicle for speed and distance measurements. Custom interface devices enable distance pulses to be stored on both the video and FM recorders.

v) A personal computer for processing the data.

vi) The vehicle is equipped with heavy duty air conditioning, a generator to supply electrical power, racks with vibration-isolation mounts for the electronic equipment.

Figure 4/ Exterior of DART vehicle

Figure 5/ Interior of DART vehicle

A schematic of the components of the radar and the thermography is given in Figures 6 and 7 respectively.

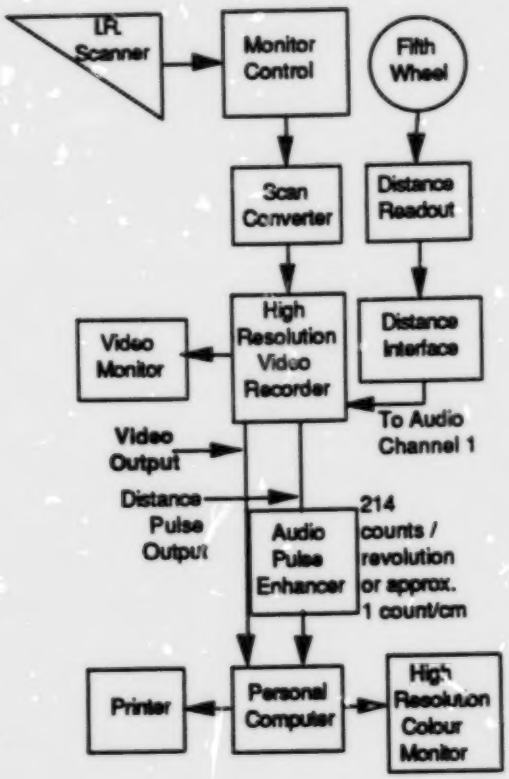

Figure 6/ Infrared system schematic

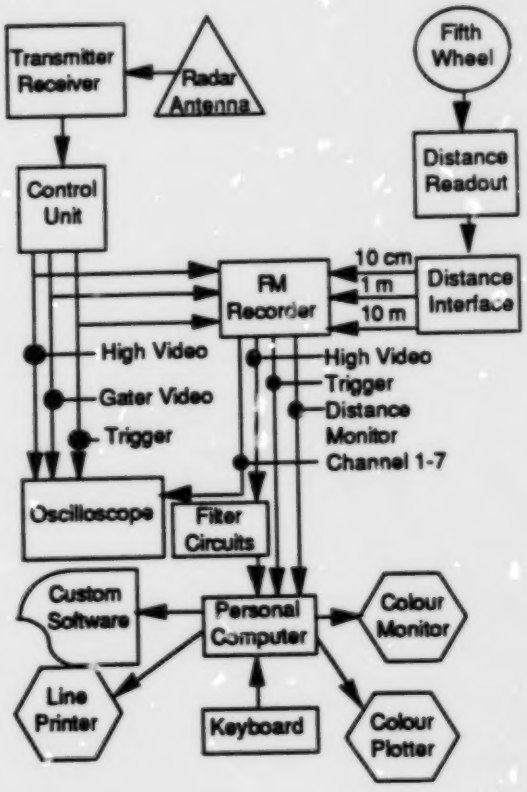

Figure 7/ Radar system schematic

4.1/ Data Acquisition/Processing

Radar

A central problem in the system software development is reducing the volume of radar data while preserving all desired information. This data reduction task faces a major problem, namely, the data recorded by the tape recorder is played back into the computer at a certain speed. Some control is permitted in that the tape speed is selectable and the recorder may be started and stopped when necessary. In addition, the tape may be rewound in order to read data starting at any location. Nevertheless, the input data stream must be stored using a large memory.

Initially, it was intended to use the DART system hard disk unit as a mass storage unit (up to 10 megabytes) for random access storage from the input. This unit, however, cannot be filled with data in real time due to the DOS overhead, and also due to the computer being based on a single processor machine. In essence, data cannot be sampled into computer memory and transferred onto the hard disk simultaneously.

The alternative is to input a portion of data into computer memory, and then stop the tape recorder while the data are transferred from computer memory onto the hard disk. The process can then be repeated by starting the tape recorder again and so on until the whole bridge deck has been sampled. Using the computer memory as an intermediate data buffer in this way has been done successfully with assembly language programming. Assembly language was necessary to handle the high speed requirement of data sampling and data management essentially in real time. Approximately 410,000 bytes of data can be sampled into the computer memory buffer before the tape recorder must be stopped while the data are off-loaded onto a hard disk file.

Data reduction in the data acquisition programs is accomplished in two different ways. First, for all waveforms only 10 ms of data before and after the surface reflection is considered relevant. After internal noise subtraction, only the second 10 ms of data are permitted to enter data processing subroutines. The second 10 ms slot is also used to compute the average level of the trace and to zero-average adjust the trace. Secondly, for data that are processed using fifth wheel information, the 10 cm fifth wheel waveform is used to ensure that waveforms are sampled only every 10 cm.

Thus, regardless of the speed of the van (provided that at least two traces are always available), the data set entering the computer is kept to a near minimum. This is especially important where slow van speed can cause huge quantities of redundant data.

With these data reduction techniques, it is possible to load computer memory with 225 separate radar traces which correspond to 45 m of bridge deck. At this point, the tape recorder must be stopped to allow off-loading of the data onto the hard disk in the form of a raw-data binary file. These raw-data binary files are used subsequently as inputs to the detailed processing programs.

The program MTO88, written in standard Fortran 77 language, performs all processing functions such as calculating the depth of asphalt, determining the R1/R2 ratios for scaling and debonding, and providing the zero crossing count for delamination detection. The software is designed to handle analysis for a bridge deck of any length with 12 grid lines. The processed results are stored as

formatted data files for future reference and are also output, in tabular form, to the monitor screen and the line printer.

Thermography

For processing the data, the video record is fed into an on-board computer through an image digitizer interface. Using custom software, the infrared image is sampled in such a way that the oblique angle of view and other distortions of the infrared image are eliminated. Deterioration is identified through a combination of computer- and operator-assisted machine interpretation [6]. The computer produces a scaled graphics image of each lane of the deck, showing areas of delamination and scaling.

5/ Field Operations and Experience

The DART vehicle is normally operated between May and November, with the infrared scanner being rented only for the months of June, July, and August. However, the scanner has also been used in February to investigate its application in cold weather.

The vehicle is operated at a speed of between 3 and 8 km/h. At faster speeds, the digitized version of the infrared image is distorted and the radar surface coverage capability is impeded.

Whereas one pass with the equipment permits an infrared scan of one complete lane width, the radar collects information only along a grid line approximately 300 mm wide. The number of grid lines required with the radar is a function of the condition of the deck (the worse the condition of the deck, the more grid lines are needed). In general, a minimum of two passes are made in each traffic lane. The data are analyzed using a "quick-look" version of the software which samples data every 10 m along each grid line and the processing is completed in a few minutes. If the "quick-look" program indicates significant deterioration, additional passes are made and, on badly deteriorated decks, a grid-line spacing of as little as 1 m may be used. The "quick-look" program also enables the operator to verify the quality of the data.

Traffic protection and lane closures are required for the safe operation of the DART equipment. The extent of the traffic protection and the number of lanes closed at any one time, depends upon specific site conditions. On a typical two-lane bridge with a heavy volume of traffic, the time taken to set up the traffic protection usually exceeds that taken to complete the infrared and radar surveys.

For the purposes of discussing the operating characteristics of the prototype unit, it is convenient to describe the experience gained with the infrared thermography and the radar separately.

5.1/ Thermography

In general, areas of delamination on exposed concrete decks can be identified at almost any time of day except near sunrise and sunset. Near sunrise, the surface temperature of the delamination changes from being cooler to hotter than the average deck temperature. The reverse situation occurs shortly after sunset. The "window" in which delaminations can be detected through a 80 mm thickness of bituminous concrete is quite narrow. The optimum time (in Southern Ontario) is between 12:00 am and 1:00 pm when the delaminations are not only most easily distinguished, but the area of the "hot spots" approximates the actual size of the delaminated areas. Although, the maximum difference in temperature usually

occurs later in the day, the outline of the delaminations becomes less distinct because of heat transfer within the surfacing. After about 3:00 pm, the deck begins to cool and the delaminations fade and are no longer detectable by the scanner.

Infrared scanning should be limited to days with no more than 10% cloud cover. Cloud cover reduces solar radiation and the temperature differences which develop. The passage of clouds while operating the scanner changes the grey scale of the images. This means that it is not possible to set a specific level associated with deterioration which is consistent for the total area of the bridge deck. The operator must also be aware of the effect of shadows cast by such objects as overhead signs or trees.

Studies elsewhere [6] have indicated that high winds effectively neutralize differences in surface temperature and this is supported by theoretical calculations [7] The effect in field measurements was, however, less than anticipated and a successful survey was made under clear skies with winds gusting to 55 km/h recorded on an anemometer located 2 m above the deck surface. A survey was also made under steady wind conditions of 50 km/h. In both cases, the deck was asphalt-covered. From these observations, it was concluded that, under clear sky conditions, wind velocities of up to 50 km/h will not affect infrared surveys significantly.

The optimum time of year for infrared bridge testing will depend upon local climate and latitude. In southern Ontario, maximum temperature differentials were observed in early or late summer when clear skies prevailed, rather than in mid-summer when overcast conditions were more prevalent. Ambient temperature in the range of -33°C (in February) to 32°C were investigated and were found to not have a significant effect on the detectability of deterioration. Differentials were, however, greater in summer than winter because of the greater intensity of solar radiation.

Studies have shown that infrared thermography cannot be used if moisture is present on the surface. Furthermore, precipitation preceding the survey must be considered. If the bituminous surfacing contains water, or water is present in delaminated or scaled areas of older decks built with an imperfect membrane, the water affects the transfer of heat into the deck and deterioration will either not be detected or not be amenable to the normal interpretation.

As a rule, delamination, scaling, and debonding can be detected when all asphalt surfacing is less than 75 mm thick. At greater thicknesses, the detection of deterioration becomes uncertain.

Although the equipment has a sensitivity of about 0.1°C, a temperature differential of 1.5°C to 2°C is a reasonable practical minimum to counteract the effects of differences in emissivity caused by such factors as polishing in the wheel tracks, staining, and patching.

Thermographs taken of the same deck on different days will not be the same. Not only will weather conditions not be precisely the same, but any change in the absorptivity of the deck surface will also affect the thermograph.

Normal traffic density was not found to affect the infrared inspection technique significantly. Normal traffic on adjacent lanes did not influence the results. Transient shadows of large vehicles were observed at some sites, but these moved rapidly enough not to affect the infrared image. However, if the traffic density is sufficient to lower the solar irradiance reaching the deck surface, temperature differences are affected. Such a condition existed during the survey of one bridge on an urban freeway where lane closures resulted in bumper-to-bumper traffic in the lanes which remained open. When the traffic protection was changed to allow the survey of the lanes subject to heavy traffic, delaminations were not readily identified and between the wheel tracks there was a noticeable heating effect from the engines of slow-moving vehicles.

Accumulations of debris on the surface, particularly sand remaining from winter maintenance operations and concentrated near the curbs, will affect infrared surveys. If this condition exists, the bridge deck should be swept the day before the actual survey.

Infrared surveys should always be performed before radar surveys. This is because any obstructions to solar radiation on the bridge, such as people or stationary vehicles, can cause false readings in the infrared image. A typical infrared output for a delaminated deck is shown in Figure 8.

Figure 8/ Infrared output for a portion of one lane (Dark areas are delaminations)

5.2/ Radar

Investigations have been made to assess the radar's operating characteristics under a range of climatic conditions on a variety of structures.

The major advantage of radar is the ability to propagate through layered media, thereby giving information on bituminous surfacings, concrete deck slabs, the interface between the two, and any discontinuties. In fact, a bituminous surfacing more than 25 mm thick enhances waveform interpretation (compared with an exposed concrete deck) because interference between the radar echo reflected from the deck surface and the radar echo from deterioration below the surface is reduced substantially. On exposed concreted ridge decks, reflected signals from defects interact with surface returns. The Ministry's existing software is applicable only to asphalt-covered bridge decks. Typical radar software output for a deck is shown in Figures 9 to 12.

Unlike the infrared system, radar has the advantage that it is virtually independent of weather conditions, and is well suited for use on asphalt-covered decks. It can also identify defects which cannot be detected by infrared thermography. However, it is less well suited for use on exposed concrete decks for the reason previously cited. The major disadvantage of radar is that it produces data along the lines which are traversed by the antenna. Consequently, unless several passes are made, areas of deterioration can be missed. On the other hand, infrared thermography can be used only when differences in surface temperature exist; however, it provides complete deck coverage. Its only real disadvantage is its dependence on the weather which is especially true for asphalt covered decks. A comparative evaluation of the relative strengths and weaknesses of the DART's radar and infrared systems is provided in Table 1.

It is apparent from Table 1 that the radar and infrared systems used in the DART prototype complement each other very well. Taken separately, the radar system provides only the dimension of depth, while the infrared thermography provides a two-dimensional surface image. By using both techniques, it is possible to obtain a three-dimensional perspective of the condition of a bridge deck.

Figure 9/ Survey summary for a typical bridge deck

[SUMMARY]

DATE = 10 31.1990 TIME = 13:44: 4:31

NINTH LINE BRIDGE DECK site 10-82-327 north bound direction

AVERAGe Bridge Length = 64.9 metre NUMBER of LINES processed = 10

metre	1		2		3		4		5		6		7		8		9		10	
1	86	81	82	83	72	65	76	67	64	69	93	54	83	73	72	71	75	62	88	72
2	125	87	79	77	117	73	105	73	105	95	113	122	105	79	110	70	98	71	103	79
3	86	76	92	69	113	73	109	77	104	104	111	62	108	79	114	69	100	71	103	77
4	94	77	94	68	113	75	111	75	104	119	105	79	107	80	112	71	100	77	105	74
5	83	77	121	79	109	75	107	75	105	125	115	99	106	87	110	72	99	76	106	75
6	112	73	117	76	108	76	106	74	107	110	115	125	108	87	110	70	98	75	113	71
7	113	83	112	77	105	76	101	77	103	105	110	62	106	79	100	78	91	77	108	70
8	115	88	109	82	102	74	100	79	99	75	110	61	105	77	90	86	88	80	105	69
9	104	76	107	80	103	73	100	75	98	120	109	72	105	76	101	71	94	67	108	68
10	116	86	106	82	101	70	98	73	98	111	110	136	103	76	103	66	95	69	109	67
11	114	81	107	75	103	67	98	74	99	70	111	114	96	80	95	71	95	72	108	74
12	113	78	109	69	104	65	101	71	97	63	112	93	101	75	98	71	90	79	108	78
13	114	90	108	71	102	65	99	69	94	67	110	109	103	73	109	63	79	89	99	83
14	114	79	109	71	95	69	95	69	96	85	107	97	102	73	105	62	76	88	105	74
15	110	83	110	70	101	64	100	69	92	92	93	95	97	75	103	63	88	70	109	65
16	112	83	110	74	102	68	103	58	90	85	94	96	97	83	104	53	85	78	105	75
17	116	83	113	74	101	70	97	75	90	85	98	92	94	82	90	81	82	77	109	71
18	109	85	107	76	91	77	84	84	93	83	99	87	78	87	80	75	74	82	84	90
19	107	92	111	76	102	63	100	74	91	78	101	86	86	93	74	83	95	82	114	57
20	109	95	105	82	97	68	100	66	86	87	102	86	97	72	104	60	77	81	94	83
21	110	93	108	83	101	63	103	77	90	82	102	85	91	76	103	57	89	67	102	73
22	116	89	113	78	100	64	95	71	85	85	95	92	86	78	89	71	82	74	114	68
23	112	90	98	91	90	75	99	83	89	75	87	86	84	77	83	79	94	64	115	66
24	83	71	110	70	90	72	101	88	93	90	88	64	89	76	98	65	90	64	109	71
25	114	75	99	80	84	80	100	92	82	81	95	69	84	76	97	62	85	71	108	73
26	107	76	93	80	85	81	95	104	79	76	87	64	86	86	98	73	88	64	116	64
27	102	86	95	82	86	80	90	113	85	71	80	70	87	68	101	64	81	74	123	60
28	105	87	108	75	89	77	90	113	84	64	84	69	90	66	105	63	72	90	114	73
29	108	84	108	75	94	76	86	109	81	72	90	64	85	69	100	74	93	77	105	80
30	109	84	111	73	93	74	96	99	83	70	91	63	90	72	103	75	93	77	94	89
31	108	84	110	73	97	65	108	101	85	69	93	64	90	63	104	74	91	79	103	82
32	108	79	108	71	98	72	105	109	81	70	100	61	95	65	101	73	94	75	104	82
33	107	78	107	71	99	71	105	110	89	70	96	61	94	66	104	62	96	68	105	78
34	107	81	112	70	101	70	110	113	89	68	95	62	95	62	109	69	100	92	112	68
35	108	82	109	72	103	70	110	121	92	61	95	60	95	63	111	60	104	65	117	70
36	111	83	108	71	104	70	107	123	92	65	96	60	93	65	105	68	105	72	112	85
37	110	81	108	69	98	73	98	120	90	74	94	61	93	62	105	67	103	72	105	90
38	105	89	104	71	97	62	103	102	84	92	93	64	87	95	103	64	101	73	100	97
39	105	84	103	69	88	68	99	93	82	93	92	63	85	90	99	70	96	71	102	86
40	107	80	106	64	93	94	97	68	82	89	91	97	82	86	93	73	96	72	109	80
41	108	77	110	62	94	97	97	69	83	87	92	96	87	78	93	75	100	71	111	85
42	108	81	107	71	88	66	98	73	85	87	91	97	88	77	96	71	99	74	114	80
43	105	82	104	73	89	70	100	74	83	87	92	94	86	75	95	70	99	70	111	76
44	79	90	103	75	95	74	96	77	83	86	94	85	87	57	92	70	99	71	109	82
45	79	103	105	75	98	74	100	77	86	85	94	88	82	69	95	62	98	69	111	79
46	83	101	106	75	102	74	102	78	84	89	91	94	81	77	93	65	98	66	111	77
47	111	77	105	78	96	77	101	81	82	94	90	98	82	77	91	69	101	66	112	72
48	109	81	103	79	93	75	96	80	83	93	91	84	84	78	97	63	102	70	113	85
49	108	82	99	80	90	75	96	77	82	92	90	89	84	83	98	68	102	72	76	79
50	108	79	99	78	92	75	95	76	82	90	92	95	92	75	97	76	102	77	80	77
51	110	77	100	79	90	76	97	74	84	87	93	93	95	74	103	70	105	74	81	76
52	109	77	98	79	94	72	98	71	83	84	92	96	91	79	102	72	101	75	118	81
53	110	82	98	81	95	71	98	76	83	90	94	91	89	83	97	75	99	75	112	85
54	111	80	97	80	94	78	101	78	78	98	98	103	88	83	94	74	99	74	111	82
55	112	76	100	76	100	73	106	74	79	95	95	96	85	80	90	72	91	84	111	83
56	107	81	98	78	96	75	105	73	83	91	94	93	85	77	89	76	93	78	112	75
57	112	80	106	78	99	70	103	67	89	79	91	90	85	74	90	73	88	77	113	69
58	109	83	109	78	95	72	100	85	87	78	89	91	86	73	91	69	92	83	116	66
59	109	92	108	85	99	70	104	65	94	77	91	90	86	78	86	80	93	82	115	70
60	113	95	106	85	96	74	102	67	95	76	90	92	83	79	77	84	79	80	113	71
61	113	91	108	81	94	78	79	90	84	87	61	85	81	80	81	81	74	84	105	72
62	107	87	106	81	97	74	74	93	94	77	74	85	84	82	77	83	74	84	94	75
63	103	87	99	78	98	74	100	79	91	82	68	85	85	84	80	84	82	77	90	76
64	99	81	102	73	93	73	98	80	85	89	86	80	81	88	71	89	76	74	89	71

[SUMMARY]

NINTH LINE BRIDGE DECK site 10-82-327 north bound direction

DATE = 10 31.1990 TIME = 13:44:18:53

[FLAT PLATE AMPLITUDE] = 7.926542 v
[FIFTH WHEEL] = 10.000000 co
[ASPHALT core sample] = 100.0 mm
[CONCRETE core sample] = 85.0 mm

[AVERAGe DIELECTRIC CONSTANT OF ASPHALT]

1	2	3	4	5	6	7	8	9	10
6.65	6.55	6.95	7.01	7.73	6.34	6.61	6.39	7.56	6.88

[AVERAGe ASPHALT THICKNESS]

	1	2	3	4	5	6	7	8	9	10
millimetres	106	104	97	99	88	95	91	96	91	106

[AVERAGe CONCRETE COVER]

	1	2	3	4	5	6	7	8	9	10
millimetres	83	76	73	83	85	84	77	72	75	76

[PERCENTAGE OF DAMAGES]

	1	2	3	4	5	6	7	8	9	10
SCALed	.00	.62	9.05	.00	5.97	9.12	2.63	.00	.00	.00
DELAMINAted	.15	.77	1.39	.31	7.20	6.96	7.26	7.06	3.24	3.09
DEBONDed	.00	1.39	2.61	.15	20.98	9.43	.00	.00	.15	.62
DAMAGED	.15	2.77	13.65	.46	34.15	25.50	9.89	7.06	3.39	3.70

[CONDITIONS]

	1	2	3	4	5	6	7	8	9	10
DAMAGED	.15	2.77	13.65	.46	34.15	25.50	9.89	7.06	3.39	3.70
GOOD	99.85	97.23	86.35	99.54	65.85	74.50	90.11	92.94	96.61	96.30
CORRUPTed	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

[OVERALL AVERAGES]

[dielectric constant of asphalt] = 6.866960

[asphalt thickness (mm)] = 97

[concrete cover (mm)] = 78

[PERCENTAGE of DAMAGES]

SCALED 2.74 %
DELAMINATED 3.80 %
DEBONDED 3.53 %

DAMAGED 10.07 %

[CONDITIONS]

DAMAGED 10.07 %
GOOD 89.93 %
CORRUPTED .00 %

TOTAL 100.00 %

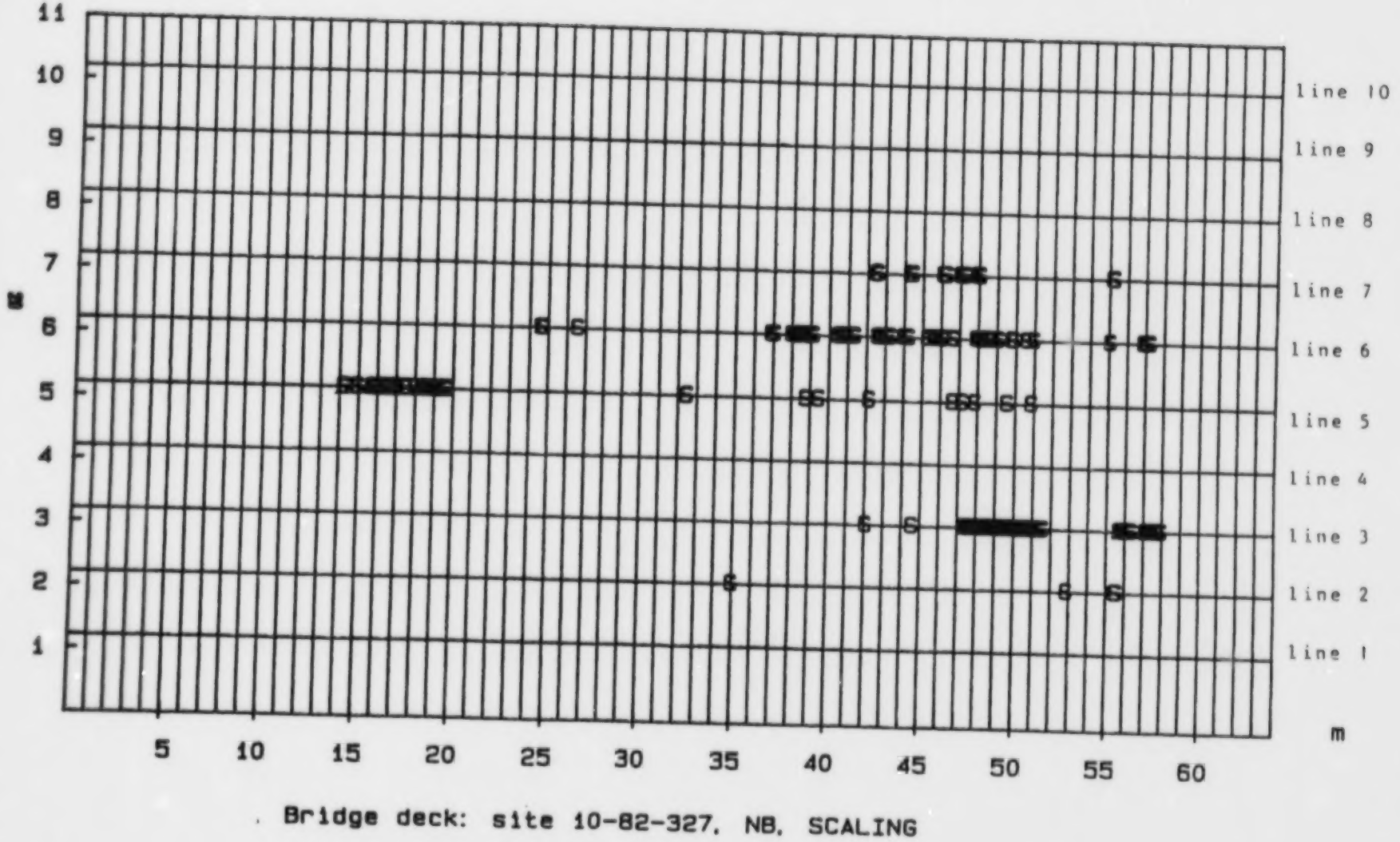

Figure 10/ Scaled areas detected by radar waveform interpretation

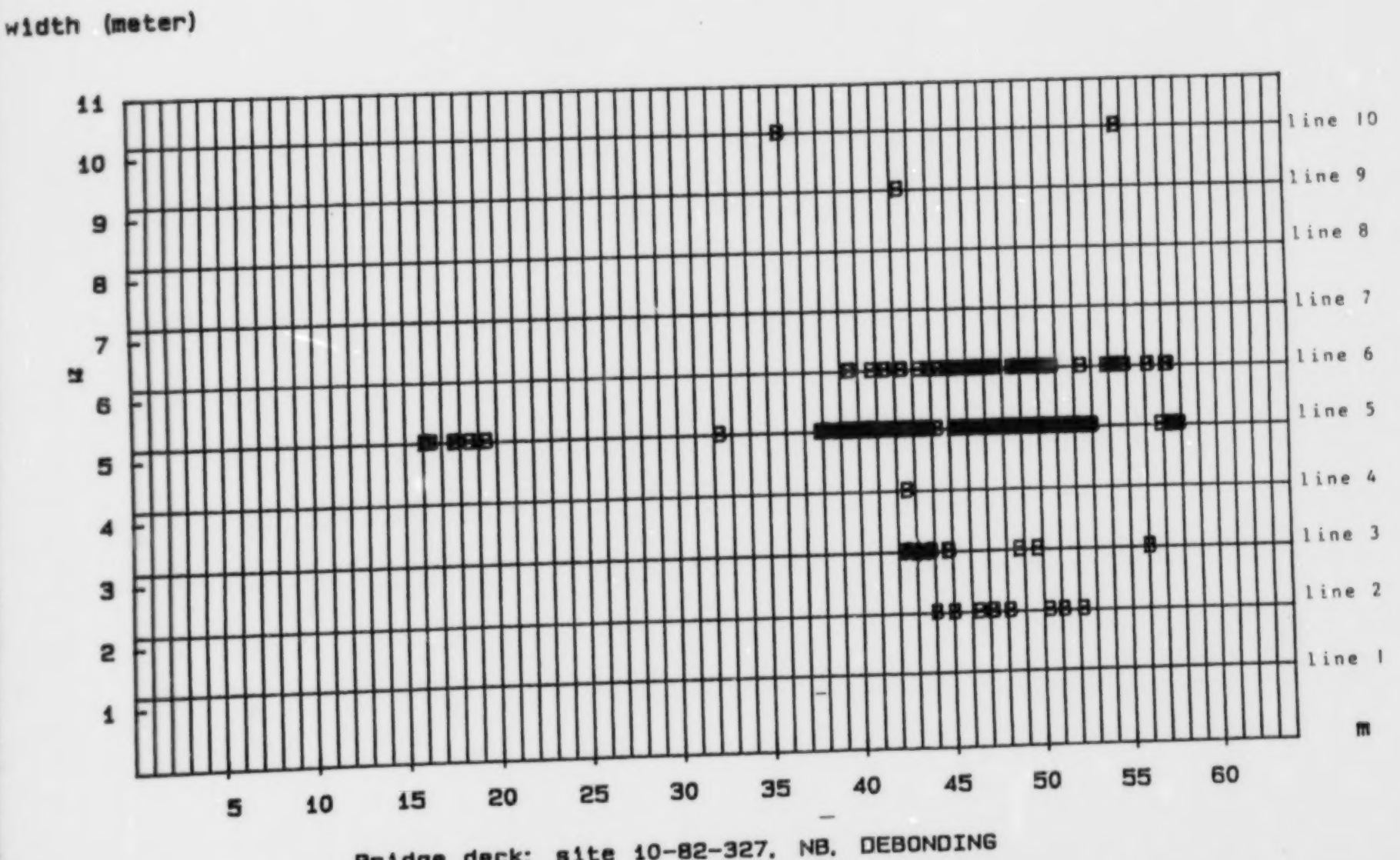

Figure 11/ Debonded areas detected by radar waveform interpretation

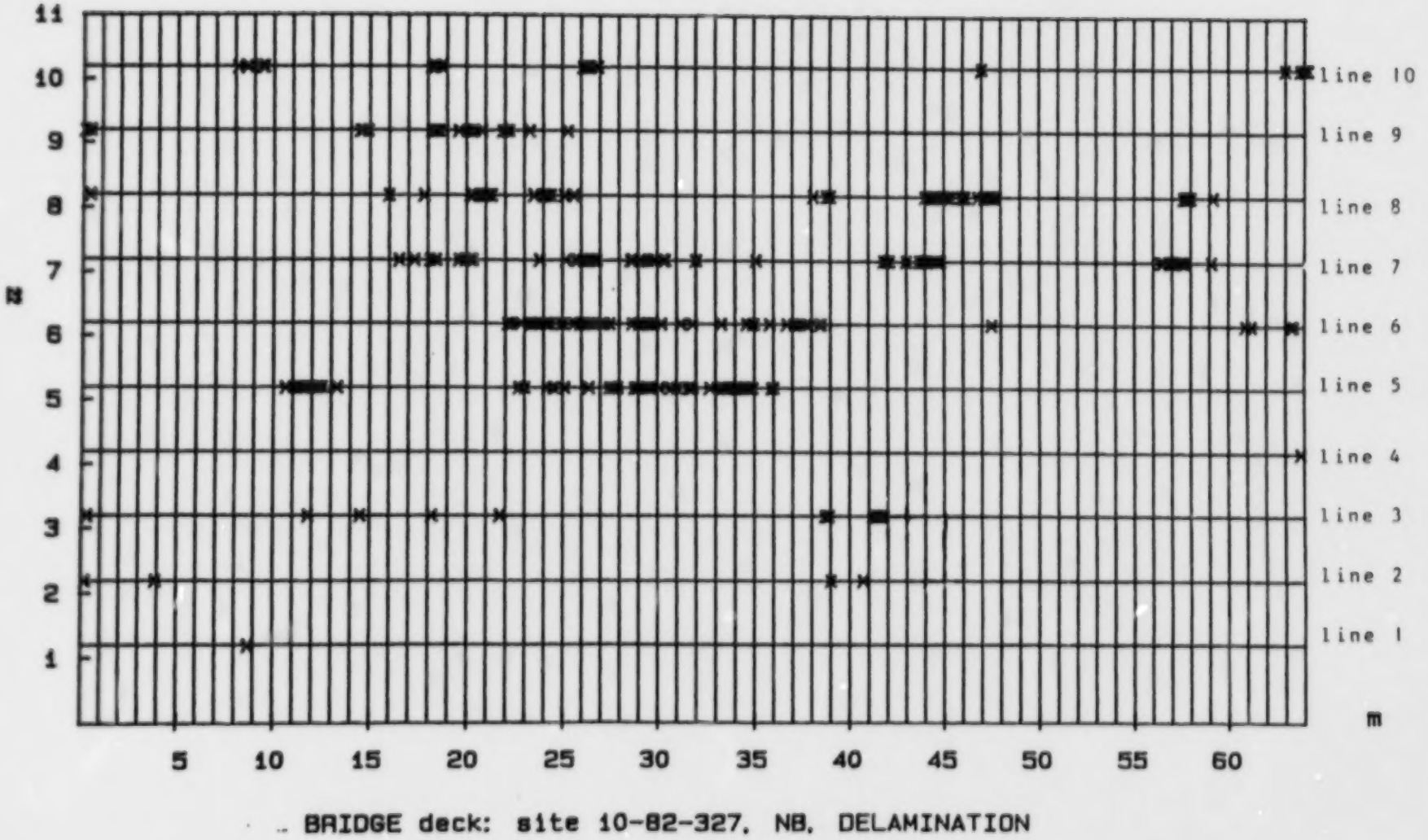

Figure 12/ Delaminated areas detected by radar waveform interpretation

Table 1/ Operational characteristics of radar and infrared thermography

Operational characteristic	Effect	
	Radar	Infrared
Meterological limitations	Adversly affected by standing water only.	Needs sun, low wind velocity. Inoperable with standing water
When can system be used?	Year round	Year round but must have sun and no rain
What hours of the day can system be used?	All day	Ideally 9:00 to 15:00
Influence of external parameters: *paint markings* *isolated debris* *oil stains* *skid marks* *snow/ice/water* *traffic*	 none none none none adverse none	 easily compensated for easily compensated for easily compensated for none adverse adverse if solar irradiance affected
Signal noise level	Waveforms need careful monitoring and calibration	Hot spots may not be detected due to meteorological factors or secondary reflections
Signal reproducibility	Independent of time, excellent	Dependent on solar heating, variable
Selectivity: *Asphalt covered deck* *Exposed concrete decks*	 Excellent results with overlay >25 mm Signal processing software not applicable	 Good if <75 mm overlay Excellent results
Penetration	Detects deep seated effects; difficulty with surface effects	Detects only surface effects; no penetration
Surface preparation	None	Monitoring of solar obstructions. Surface cleaning may be required.
Inspection speed (limiting factors)	Maximum 8 km/h (pulse repetition rate)	Maximum 4.5 km/h (video digitization rate/camera scan rate)
Number of scans required	Many, depending on bridge width and coverage required	One scan per lane
Support personnel required	High level of technical competence	Basic training plus experience on bridges
Traffic protection	Necessary	Necessary

6/ Costs

The DART system represents a significant investment. The value of the major items is summarized below; however, because of customs duties, fluctuations in exchange rates, and volatility in the price of electronic components, the following costs (in 1989 Canadian dollars) should be regarded as approximate:

Radar	$75,000
Thermal Scanner and Converter	$54,000 (or $2400 per month rental)
Microcomputer and Peripherals (including extra circuit boards)	$27,000
FM Recorder	$13,000
Industrial VCR	$ 5,000
Fifth-Wheel	$ 7,000
Oscilloscope	$ 2,400
Generator	$ 1,500

Adding the cost of the vehicle, generator, external and interior racks, and numerous smaller items such as cables, filters, and interface devices, would make the replacement cost of the fully equipped DART vehicle approximately $180,000. It should be noted the Ministry did not purchase the thermal scanner and converter, but rented the equipment during the summer months for $2,400 per month. In addition, the cost of developing the software was $96,000 for the radar and $30,000 for processing the thermal images.

7/ Concluding Remarks

The first year's experience with the DART system has shown that, within known limitations, the prototype constitutes a viable rapid non-contact and non-destructive method for performing condition surveys. At present, the DART prototype is not in a "push button mode" and requires a high level of skill and expertise to operate. However, even at this stage of development, it is realistically possible to perform 150 to 200 condition surveys a year. It is envisaged that the system will play a major role in providing data for the Ministry's bridge management system. In addition, the system will permit a reduction in the scope, and therefore a cost saving, in detailed bridge condition surveys which are made once a bridge is scheduled for rehabilitation. Furthermore, the opportunity to collect reliable data on the thickness of bituminous surfacings and the depth of cover in asphalt covered deck slabs affords an opportunity to simplify contract administration and lower prices by reducing the uncertainty in bid items.

Future work will involve upgrading the personal computer. This will not only increase the processing speed, but the enhanced memory will eliminate the need for the FM recorder. Any other changes are likely to focus on making the system simpler to operate.

Other studies will be undertaken to determine the feasibility of applying radar to other components of bridge structures and to pavements.

8/ References

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